Discovery of inward moving magnetic enhancements in sunspot penumbrae

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ABSTRACT

Sunspot penumbrae show a fine structure in continuum intensity that displays considerable dynamics. The magnetic field, in contrast, although also highly structured, has appeared to be relatively static. Here we report the discovery of inward moving magnetic enhancements in the penumbrae of two regular sunspots based on time series of SOHO/MDI magnetograms. Local enhancements of the LOS component of the magnetic field in the inner part of the penumbral region move inward to the umbra-penumbra boundary with a radial speed of about 0.3 km s^{-1}. These local inward-moving enhancements of the LOS component of the magnetic fields appear to be relatively common. They are associated with dark structures and tend to display downflows relatively to the penumbral background. Possible explanations are discussed.

Subject headings: Sun: sunspots —Sun: atmospheric motions —Sun: magnetic fields

1. INTRODUCTION

Sunspot penumbrae are both, structured in a complex manner and highly dynamic. They display fine structure in the form of dark and bright fibrils (the latter with dark cores; Scharmer et al. 2002) and bright points, called penumbral grains. Dynamic features associated with the penumbral photosphere are the horizontally outward directed Evershed flow, the outward motion of dark clouds that seem to dominate the outer penumbra (Shine et al. 1994) and the steady inward motion of penumbral grains (e.g. Muller 1976;

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Sobotka, Brandt, & Simon 1999), as well as oscillations (e.g. Musman, Nye & Thomas 1976; Bloomfield et al. 2007). See Solanki (2003) for a review.

The magnetic field, just like the brightness, also displays a complex structure in the penumbra, with interlaced regions of horizontal and more inclined field lying nearly parallel to penumbral fibrils (Degenhardt & Wiehr 1991; Title et al. 1993). These have been interpreted in terms of horizontal flux tubes embedded in an inclined field (uncombed field; Solanki & Montavon 1993; cf. Bellot Rubio, Balthasar & Collados 2004; Borrero et al. 2005, 2006) and of field-free gaps between the field lines (Scharmer & Spruit 2006).

Unlike the brightness structure, there has so far been little evidence for significant, persistent changes of the fine-scale magnetic structure of the penumbra. In fact, the magnetic pattern has been found to change little over a period of an hour (Solanki & Rüedi 2003). The main exception is the outward motion of magnetic enhancements that later move into the moat and become Moving Magnetic Features (MMFs) (Sainz Dalda & Martínez Pillet 2005). Here we present the first observation of inward moving magnetic enhancements in penumbrae and determine their continuum brightness signature.

2. OBSERVATIONS

The data sets analyzed here consist of magnetograms, Dopplergrams and continuum images, obtained by the Michelson Doppler Imager (MDI, Scherrer et al. 1995) onboard the *SOHO* spacecraft, operated in its high-resolution observing mode with a spatial and temporal sampling of $0.6''$ and 1 minute, respectively. The targets are the active regions, NOAA AR 0330 ($\mu = 0.984$, which corresponds to a heliocentric angle θ of 10°) and NOAA AR 9697 ($\mu = 0.974$, $\theta = 13^\circ$). NOAA 0330 was observed between 2003 April 9, 14:05 UT and 2003 April 10, 00:49 UT, while NOAA 9697 was observed between 2001 Nov. 17, 18:00 UT and Nov. 18, 06:10 UT. By treating the data as Sainz Dalda & Martínez Pillet (2005) have done, i.e. selecting a square region of $180''\times180''$, compensating solar rotation and correcting for border effects, we follow the transit of a sunspot through the MDI high-resolution area. All magnetograms, Dopplergrams and continuum images are further co-aligned by searching for the maximum of their correlation with respect to a single reference magnetogram. This ensures that any proper motion of the sunspot as a whole is removed, so that the center of gravity of the spot remains roughly at the same position. Fig. 1 shows continuum images of the two studied sunspots. The rectangular frame outlines a subfield (see Fig. 2), and the solid lines 'AB' and 'CD' cross the penumbra from the inner to outer boundary at locations at which we present time slices. In the following we discuss the dynamics of the field, the brightness and the velocity in these locations.

3. RESULTS

In Fig. 2 we display a time sequence of the continuum images (left column) and the magnetograms (right column) in the subfield marked in the upper panel of Fig. 1. The light yellow continuum intensity contours outline a dark feature, the white ones the umbral boundary (see the arrow in the continuum image at 17:34 UT). These contours are overplotted onto the corresponding magnetograms. The brightness of the dark feature is about 80% of the average brightness in the penumbra and it corresponds to an enhancement in the magnetogram signal, $B_{||}$ (i.e. the LOS component of the magnetic field) seen in the right panels of Fig. 2 as a finger of enhanced brightness. The $B_{||}$ enhancement and the associated dark feature first appear in the inner half of the penumbra and move to the inner penumbral boundary with an average speed of 0.3 km s^{-1} from 17:34 UT to 19:36 UT. The arrow in the continuum image at 18:35 UT denotes the motion direction of the feature. Finally this feature intrudes into the umbra at 20:36 UT. The fact that this feature appears isolated in brightness, but only as an intrusion of high field into the penumbra has to do with the strong radial gradient in the magnetogram signal. When this gradient is removed (Fig. 3) the magnetogram enhancement becomes clearly visible.

Fig. 3 shows time-slice maps taken from the continuum images (left), the magnetograms (middle), and the Dopplergrams (right), respectively. The X-axis is the distance ($\sim$14 Mm) from 'A' to 'B' (see Fig. 1), which cuts the penumbra from the inner to the outer boundary, and the Y-axis is the time from 2003 April 9, 14:05 UT to April 10, 00:45 UT. In order to better reveal small-scale (moving) features, we make a 2-D quadratic polynomial fit to each of the upper frames. After the removal of this polynomial fit (lower frames) considerable dynamic structure becomes visible, with different features in the inner (left of the vertical white lines) and the outer penumbra. In the outer penumbra, a large magnetic feature is seen to move steadily outward with a speed of 0.25 km s^{-1} for about 7 hr. Upon leaving the sunspot it becomes an MMF. The dotted line in the lower magnetogram time-slice shows its trajectory. In the outer penumbra there is also a possible hint of small magnetic features that move outward with an average speed larger than 1.2 km s^{-1} (the arrows in the lower middle panel point in the directions of motion). These features merge with the large one and continue their outward motion together.

In the inner penumbra, however, magnetic features with larger $B_{||}$, denoted 'M1' and 'M2', move inward towards the umbra. The feature 'M1', already present at the start of the MDI observation period on 2003 April 9, 14:05 UT, persisted for 5 hr while moving to the inner boundary with a mean speed of 0.3 km s^{-1}. About two hours later, the second feature 'M2' appeared. It moved to the inner boundary with a speed of 0.35 km s^{-1}, and remained visible for 2-2.5 hr.

These inward moving features are slightly darker than average (they avoid bright features), and the Dopplergram counterparts have a tendency to show a relative red shift (brighter regions in the right-most panels of Fig. 3). In the inner penumbral region (see the lower frames of Fig. 3), there is a relationship between continuum intensity and magnetic flux density residuals (with a correlation coefficient of -0.52), as well as between continuum intensity and Doppler shift residuals (cf., Schlichenmaier & Schmidt 1999), with a correlation coefficient of -0.55.

Fig. 4 shows time-slice maps along the line CD (active region NOAA AR 9697). In the outer penumbra a feature that later becomes an MMF (see the shorter arrow in the middle panel) moves outward to the moat around the sunspot. In the inner penumbra, a larger magnetic feature denoted 'M' moves to the inner boundary with an average speed of 0.3 km s^{-1}. The longer arrow indicates the direction of motion. This feature is obviously darker than average and is associated with a slight average redshift relative to its surroundings.

Inward motion of features displaying an enhanced magnetogram signal is also found at other locations in the studied penumbrae, as well as in the main sunspot of NOAA AR 8375 in November 1998, which we also analyzed and which confirms the results found for the two sunspots presented here.

4. DISCUSSION AND CONCLUSIONS

We report on the first detection of inward moving enhancements of the magnetogram signal in the inner halves of sunspot penumbrae, associated with a local darkening and possibly a weak downflow. These features can be followed right to the umbral boundary. This phenomenon appears to be quite common, since we noticed it at numerous locations in the penumbrae of three different mature regular sunspots. We note that an enhancement in the magnetogram signal can be produced by an enhanced field strength, by a field aligned more strongly with the LOS (which, for a sunspot close to disc center, is equivalent to a more vertical field), and conceivably also by spatially unresolved variations of continuum brightness or LOS velocity. The MDI data do not allow to distinguish easily between these possibilities.

Langhans et al. (2005) pointed out that dark penumbral cores are associated with the more horizontal component of the magnetic field, while the bright component of filaments is associated with the more vertical component of the magnetic field. The magnetogram signal is lower in the dark cores than in the bright parts of penumbral filaments. This suggests that they described other features than we have studied. An enhanced $B_{||}$ associated with a

darkening in the penumbra is more likely to be related to the larger scale "spines" of more vertical field found by Lites et al. (1993, cf. Bello Gonzalez et al. 2005). It is interesting that Bello Gonzalez et al. (2005) note the presence of downflows in the spines, which strengthens the correspondence with the inward moving features that we see.

Schlichenmaier, Jahn & Schmidt (1998a,b) have proposed that the bright features in penumbrae moving toward the umbra in the inner penumbra are the locations where hot flux tubes emerge that become horizontal further out in the penumbra. It is not clear in this model whether the inward moving features are associated with an enhancement or depression of $B_{||}$. More promising is the more recent version of this model by Schlichenmaier (2003), who finds that the horizontal flux tube develops into a sea serpent, with the innermost visible part of it moving towards the umbra, while in the outer penumbra the magnetic enhancements would move outwards and presumably become visible later as MMFs. The first footpoint, at which the flux tube and the Evershed flow it carried dives below the surface again, should show a downflow and may well be cool. This model would thus explain the remarkable divergence between the inner and outer parts of the penumbra, with magnetogram enhancements in the outer penumbra moving outwards, those in the inner penumbra inwards.

We are keenly aware of the limitations imposed by the comparatively low spatial resolution of MDI, even in its high resolution mode. Future observations at higher spatial resolution are likely to uncover more of the nature of these features. An analysis of such observations is planned.

The authors are indebted to the *SOHO*/MDI team for providing the data. *SOHO* is a project of international cooperation between ESA and NASA. This work is supported by the National Natural Science Foundations of China (G10573025 and 40674081), the CAS Project KJCX2-YW-T04, and the National Basic Research Program of China under grant G2006CB806303.

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Fig. 1.— Continuum intensity images from *SOHO*/MDI showing the main sunspots belonging to active regions NOAA AR 0330 (top) and AR 9697 (bottom). The field-of-view of both frames is about $70'' \times 70''$. The white window denotes a sub-area of the inner penumbral region where a dark feature with an enhanced magnetogram signal moves towards the umbra (see Fig. 2). The solid lines 'AB' and 'CD' cut the penumbrae from the inner to outer boundary. Time slices of measured quantities along these lines are shown in Figs. 3 and 4. The arrows point to disk center.

Fig. 2.— Time sequence of continuum images (left column) and the corresponding magnetograms (right column) in the field-of-view ($9'' \times 6''$) of the window marked in Fig. 1. The continuum intensity contours are overplotted also on the corresponding magnetograms. The dynamic ranges are from 1400 counts pixel^{-1} to 2200 counts pixel^{-1} for the continuum images and from 400 G to 1100 G for the magnetograms. The arrows are described in the text.

Fig. 3.— Time-slice maps taken from the continuum images (left), from the corresponding magnetograms (middle) and Dopplergrams (right), respectively. For each map, the X-axis represents the distance ($\sim$14 Mm) from 'A' to 'B' (see Fig. 1), which cuts the penumbra from the inner to outer boundary (left to right). The Y-axis denotes time, running from 2003 April 9, 14:05 UT to April 10, 00:45 UT (from bottom to top). The upper frames show original data, with the colour scale ranging from 1200 counts pixel^{-1} to 2400 counts pixel^{-1} for the continuum map, from 150 G to 1000 G for the magnetogram map, and from -180 m s^{-1} (black, blue shift) to 180 m s^{-1} (white, red shift) for the Dopplergram map. The lower frames display relative signals which are obtained after subtracting a second-degree polynomial surface fit from the original data. The dynamic ranges are from -100 counts pixel^{-1} to 100 counts pixel^{-1} for the continuum map, from -100 G to 100 G for the magnetogram map, and from -120 m s^{-1} to 120 m s^{-1} for the Dopplergram map. The 80 G contour overplotted on all time slices, refers to the filtered magnetogram signal in the lower-middle map. The vertical white lines on the lower maps separate inward moving magnetic features (denoted by 'M1' and 'M2') from those moving outward. The dotted line and the arrows are described in the text.

Fig. 4.— Same as the lower 3 frames in Fig. 3 but for the main spot of active region NOAA AR 9697. The X-axis represents the distance ($\sim$14 Mm, from 'C' to 'D' in Fig. 1) from the inner to outer penumbral boundary (left to right). The Y-axis denotes the time running from 2001 Nov. 17, 19:51 UT to Nov. 18, 06:00 UT (bottom to top). 'M' denotes an inward moving magnetic feature, the black arrow its direction of motion, the white arrow an outward moving feature.